Physical Properties of Near-Earth Objects

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The population of near-Earth objects (NEOs) contains asteroids, comets, and the precursor bodies for meteorites. The challenge for our understanding of NEOs is to reveal the proportions and relationships between these categories of solar-system small bodies and their source(s) of resupply. Even accounting for strong bias factors in the discovery and characterization of higher-albedo objects, NEOs having S-type spectra are proportionally more abundant than within the main asteroid belt as a whole. Thus, an inner asteroid belt origin (where S-type objects dominate) is implied for most NEOs. The identification of a cometary contribution within the NEO population remains one of a case-by-case examination of unusual objects, and the sum of evidence suggests that comets contribute at most only a few percent of the total. With decreasing size and younger surfaces (due to presumably shorter collisional lifetimes for smaller objects), NEOs show a transition in spectral properties toward resembling the most common meteorites, the ordinary chondrites. Ordinary chondritelike objects are no longer rare among the NEOs, and at least qualitatively it is becoming understandable why these objects comprise a high proportion of meteorite falls. Comparisons that can be performed between asteroidal NEOs and their main-belt counterparts suggest that the physical properties (e.g., rotation states, configurations, spectral colors, surface scattering) of NEOs may be representative of main-belt asteroids (MBAs) at similar (but presently unobservable) sizes.

1. INTRODUCTION

Planetary science investigations of asteroids, meteorites, and comets all have a common intersection in the study of near-Earth objects (NEOs), represented schematically in Fig. 1. (Here we define a NEO as an object having a perihelion distance of ≤1.3 AU.) Dynamical calculations (see *Morbidelli et al.,* 2002; *Bottke et al.,* 2002a) show that lifespans for NEOs are typically a few million years, eventually meeting their doom by crashing into the Sun, being ejected from the solar system, or impacting a terrestrial world. With such short lifetimes, NEOs observed today cannot be residual bodies that have remained orbiting among the inner planets since the beginning of the solar system. Instead, the NEO population must have some source of resupply. Understanding the source(s) and mechanism(s) of their resupply is one of the fundamental scientific goals for NEO studies. Key questions include the following: What fraction comes from the asteroid belt? What fraction of the NEOs that do not display a coma or a tail are in fact extinct or dormant comet nuclei? Pinpointing the source regions of NEOs is also a matter of high scientific priority for fully utilizing the wealth of information available from laboratory studies of meteorites (e.g., *Kerridge and Matthews,* 1988). The immediate precursor bodies for meteorites are, by definition of proximity, NEOs objects. Thus, the scientific goal of understanding the source(s) for NEOs is identical to the goal of finding the origin locations for meteorites. A key component in tracing meteorite origins is discovering links between the telescopically measured spectral (compositional) properties of asteroids with those measured in the laboratory for meteorites (see *Burbine et al.,* 2002).

The proximity of NEOs also makes them worlds for which we have substantial practical interest. Those having

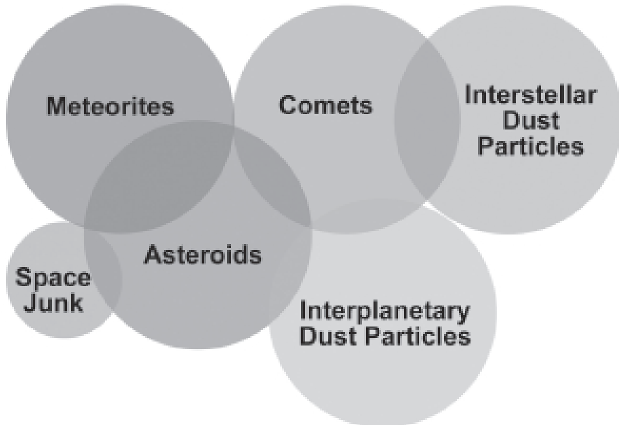

Fig. 1. Cartoon illustration of the many different groups of objects found within near-Earth space. One of the principal objectives for studying NEOs is to understand how these groups may be related. Thus the regions of intersection denote key research areas. As surveys increase their capabilities, human-made space flight hardware ("space junk") is also being increasingly found.

low-inclination and low-eccentricity orbits closest to Earth are among the most accessible spacecraft destinations in the solar system. In terms of the propulsion energy required, more than 20% of the NEOs are known to be more accessible than the Moon for long-duration sample-return missions (*Lewis and Hutson,* 1993). The fact that many NEOs remain well within the inner solar system during their orbits further simplifies thermal-design and power-generation considerations for exploratory spacecraft (*Perozzi et al.,* 2001). The proximity of NEOs also makes them prime targets for radar experiments designed to measure surface properties and achieve image reconstructions. *Ostro et al.* (2002) highlight the spectacular success of this technique and describe results for specific objects. Most renowned of the practical importance of the NEOs is the small, but nonzero, probability of a major impact that could threaten civilization. The hazard issue is addressed in *Morrison et al.* (2002), and the physical properties of NEOs as they pertain to the hazard have been reviewed by *Chapman et al.* (1994) and *Huebner et al.* (2001).

The purpose of this review chapter is to serve as a focal point for what we know about the physical properties of NEOs and how these data serve to illuminate the myriad interrelationships between asteroids, comets, and meteorites. Thus, in a way, we hope this chapter will serve as a "central node" in guiding the reader toward the interconnections that NEOs have to a broad range of planetary-science topics (and chapters within this volume). In particular, we wish to take advantage of the scientific insights that can be achieved by virtue of their proximity: NEOs are the smallest individually observable bodies in our solar system. Thus, these objects, which reside at the crossroads of many different areas of study, are also an end member to the size distribution of measurable planetary worlds. Here we draw upon, build upon, and update previous reviews by *McFadden et al.* (1989) and *Lupishko and Di Martino* (1998).

The terms used to refer to objects in the vicinity of Earth have gone through a rapid convergence as interest in them has increased over the past decade. When speaking broadly of the population, "near-Earth objects" (NEOs) has become the most widely used term, since this inclusive label does not presuppose an origin or nature as an asteroid or a comet. When speaking about objects in the vicinity of the Earth that are presupposed to have an asteroidal origin, the term "near-Earth asteroids" (NEAs) is commonly used. In this chapter we attempt not to make any general suppositions about the origins of these bodies and therefore mostly employ the term "NEO." Objects that appear "asteroidal" (starlike with no apparent coma or tail that would give them the label "comet") dominate the NEO population, with the currently known number having reasonably well-determined orbits approaching 2000 (see *Stokes et al.,* 2002). Only about 50 short-period comets (*Marsden and Williams,* 1999) satisfy the NEO definition of having a perihelion distance $\leq$1.3 AU.

Asteroidal NEOs are traditionally subdivided into groups based on their orbital characteristics a, q, Q (semimajor axis, perihelion distance, aphelion distance) with respect to Earth's and are called "Amor," "Apollo," and "Aten" asteroids (*Shoemaker et al.,* 1979). Amor objects are defined as bodies residing just outside the orbit of Earth ($a \geq 1$ AU), having $1.017 < q \leq 1.3$ AU. Objects having a semimajor axis > 1 AU and $q \leq 1.017$ AU are known as Apollos. Relatively equal numbers of Amor and Apollo asteroids are currently known; combined they account for ~90% of all currently known NEOs. Atens have orbits substantially inside that of Earth ($a < 1$ AU, $Q > 0.983$ AU), and represent about 8% of the known NEO population. (Short-period comets account for the remaining 2%.) By these definitions, Aten and Apollo objects cross the orbit of Earth while Amor objects do not. However, orbital precession, periodic variations in orbital elements, and planetary perturbations over timescales of centuries are sufficient for objects straddling the boundaries between groupings to change their affiliation. *Milani et al.* (1989) performed an orbital-evolution analysis involving 89 NEOs over a timespan of 200,000 yr. Based on these results, they propose six dynamical classes, named after the best-known and most representative object in each class: Geographos, Toro, Alinda, Kozai, Oljato, and Eros. This classification is indicative of long-term behavior and, of course, differs from the Amor-Apollo-Aten nomenclature, which is based only on the osculating orbital elements. The name "Apohele" (the Hawai'ian transliteration for orbit) has been proposed (*Tholen and Whiteley,* 1998) for one additional group of objects whose orbits reside entirely inside that of Earth ($Q < 0.983$ AU). At present only 1998 DK_{36} (*Tholen and Whiteley,* 1998) has been discovered as a potential member of this class, although this result is controversial due to uncertainties in the values of its orbital elements. *Michel et al.* (2000) refer to these as "inner-Earth objects" (IEOs) and estimate that Atens and IEOs together could constitute 20% of the multikilometer-sized Earth-crossing population.

2. TABULATION OF NEAR-EARTH-OBJECT PHYSICAL PROPERTIES

Over the past decade the growth in measurements of NEO physical properties has increased at a pace nearly commensurate with the increase in their interest and discovery rate. Physical parameters (such as spectroscopic and rotation properties) were known for only a few dozen NEOs at the time of publication of *Asteroids II* (*McFadden et al.,* 1989). An extension of this work is presented by *Chapman et al.* (1994), and a more thorough review of NEO physical properties by *Lupishko and Di Martino* (1998) summarizes results for about 100 objects, where the growth during this time period can largely be credited to the work of Wieslaw Wisniewski (*Wisniewski et al.,* 1997). Since the Lupishko and Di Martino review, a significant amount of new work has pushed the number of NEOs having (at least some) physical characterization up to more than 300 objects (e.g., *Binzel,* 1998, 2001; *Erikson et al.,* 2000; *Hammergren,* 1998; *Pravec et al.,* 2000a; *Rabinowitz,* 1998; *Hicks et al.,* 1998, 2000; *Whiteley and Tholen,* 1999; *Whiteley,* 2001).

Table 1 presents an extensive summary of the currently known physical parameters (derived primarily by spectroscopic and photometric techniques) for asteroidal NEOs. Objects are designated as belonging to the Amor (Am), Apollo (Ap), and Aten (At) groups. Mars-crossing (MC) objects of special interest are also included: 9969 Braille, encountered by the *Deep Space 1* mission in 1999 (*Oberst et al.,* 2001), and (5407) 1992 AX, a likely binary (*Pravec et al.,* 2000b). For most objects, only approximate estimates (guesses) can be made for albedos and diameters. Therefore, analyses and conclusions based on these parameters must be made with considerable caution. Taxonomic classes are from the system defined by *Tholen* (1984) and extended to include the additional designations developed by *Bus* (1999; *Bus and Binzel,* 2002; *Bus et al.,* 2002). When NIR spectral data are available such that the S-class subgroups described by *Gaffey et al.* (1993) are determined, taxonomic designations are given in this system. Rotational periods (in hours) are given if known, along with the range of lightcurve amplitudes represented by these measurements. The final columns present U-B and B-V colors, when available. Physical measurements of NEOs are certainly not limited to those parameters in Table 1, with the most exhaustive additional tabulations available in *Lupishko and Di Martino* (1998). These additional tabulations include information on individual measurements of pole coordinates, senses of rotation and asteroid triaxial shapes, photometric and polarimetric parameters, radiometric albedos and diameters, and radar parameters. More thorough information on some of these latter parameters is presented in *Pravec et al.* (2002), *Harris and Lagerros* (2002), and *Ostro et al.* (2002). Ongoing updates to Table 1, as well as citations for the references to the individual entries, may be found at http://earn.dlr.de/nea/.

3. ANALYSIS

In this analysis of the currently known physical properties of NEOs, we focus on those properties that give the best indication of origin. We particularly focus on the extent to which asteroidal NEOs may be similar to or different from main-belt asteroids in the same size range. Key differences may distinguish the relative importance of asteroid or comet origins for the population. Size dependences in the spectral properties, for example, may also illuminate links for asteroid-meteorite connections.

3.1. Taxonomy of Near-Earth Objects

Figure 2 shows the relative abundance of various taxonomic classes of NEOs, as analyzed from the data in Table 1. Note that there are subtle differences between the asteroid taxonomies derived by *Tholen* (1984) and *Bus* (1999), and these differences affect some of the identifications in Table 1. (Taxonomic designations given are as cited in the published reference.)

Almost all taxonomic classes of main-belt asteroids are represented among classified NEOs, including the P- and D-types most commonly found in the outer asteroid belt, among the Hilda and Trojan asteroids, or possibly among comet nuclei (see *Barucci et al.,* 2002; *Weissman et al.,* 2002). This broad representation of types, including those from distant regions, suggests that the processes delivering objects to the inner solar system are broad in scope (see *Bottke et al.,* 2002b; *Morbidelli et al.,* 2002). A key question we appear to be on the verge of answering is this: How significantly is the delivery of NEOs dominated by processes operating within the inner asteroid belt? S-type asteroids that dominate the inner asteroid belt also dominate the sampled NEO population by a ratio of ~4:1 (Fig. 2). This ratio, however, is subject to selection effects because S-type asteroids have higher albedos than C-types, making their discovery and observation more likely. (In a magnitude-limited survey, their higher reflectivity allows more S-asteroids to be bright enough for detection.) *Luu and Jewitt* (1989) also point out that C-type asteroids fall off in their apparent brightness more rapidly with increasing phase angle than do S-type asteroids (see *Muinonen et al.,* 2002). Since NEOs are typically discovered at larger phase angles, the coupling of this phase-angle effect with the albedo effect can create a strong bias in favor of S-type asteroids. *Luu and Jewitt* (1989) use a Monte Carlo model to estimate this bias factor to be in the range of 5:1 to 6:1.

While bias effects certainly are a major factor in creating the high proportion of S-types observed among NEOs, *Lupishko and Di Martino* (1998) argue that even after bias

TABLE 1. Physical parameters of NEOs (readers utilizing individual entries are reminded to cite the original source for each datum; original source references for each datum listed here, as well as current updates to this table, may be found at http://earn.dlr.de/nea/).

Asteroid Number*	Asteroid Name	Provisional Designation	Group	H (mag)†	Albedo‡	Diameter (km)§	Class¶	Period (hrs)	Amplitude (mag)	U-B	B-V
433	Eros	1898 DQ	Am	11.24	0.21	23.6	S(IV)	5.270	0.03–1.38	0.52	0.90
719	Albert	1911 MT	Am	15.8M	m	2.4		5.80	0.6		
887	Alinda	1918 DB	Am	13.83	0.23	4.2	S	73.97	0.35	0.43	0.84
1036	Ganymed	1924 TD	Am	9.42	0.17	38.5	S(IV)	10.31	0.12–0.40	0.42	0.84
1221	Amor	1932 EA1	Am	17.46	m	1.1					
1566	Icarus	1949 MA	Ap	15.95	0.33	1.3	SU,Q	2.273	0.03–0.18	0.54	0.80
1580	Betulia	1950 KA	Am	14.55	0.17	3.9	C	6.1324	0.13–0.65	0.27	0.66
1620	Geographos	1951 RA	Ap	16.5	0.19	5 × 2 × 1	S	5.2233	0.90–2.00	0.50	0.89
1627	Ivar	1929 SH	Am	13.24	0.26	6.9	S	4.797	0.22–1.15	0.46	0.89
1685	Toro	1948 OA	Ap	13.96	0.31	3	S	10.196	0.55–1.40	0.47	0.88
1862	Apollo	1932 HA	Ap	16.23	0.26	1.4	Q	3.065	0.12–0.70	0.43	0.79
1863	Antinous	1948 EA	Ap	15.81	0.18	1.8	Sq	4.02	0.12	0.37	0.77
1864	Daedalus	1971 FA	Ap	15.02	mh	3.1	Sr	8.57	0.80–1.04	0.50	0.83
1865	Cerberus	1971 UA	Ap	16.97	0.26	1	S	6.810	1.5–2.1	0.40	0.79
1866	Sisyphus	1972 XA	Ap	13.0M	0.14	8.9	S	2.400	0.1	0.45	0.88
1915	Quetzalcoatl	1953 EA	Am	18.97	0.31	0.4	SMU	4.9	0.2	0.43	0.83
1916	Boreas	1953 RA	Am	15.03	mh	3.1	S			0.41	0.85
1917	Cuyo	1968 AA	Am	13.9M	mh	5.2	Sl	2.6905	0.11–0.44		
1943	Anteros	1973 EC	Am	16.01	0.18	1.8	L	2.8695	0.05–0.1	0.45	0.84
1980	Tezcatlipoca	1950 LA	Am	13.95	0.14	6.7	Sl	7.2505	0.47–0.97	0.46	0.96
1981	Midas	1973 EA	Ap	15.18	h	2.2	V	5.220	0.65–0.87	0.48	0.97
2061	Anza	1960 UA	Am	16.56M	m	1.7	TCG	5.75	0.08–0.26	0.35	0.76
2062	Aten	1976 AA	At	17.12	0.20	0.9	Sr	40.77	0.26	0.46	0.93
2063	Bacchus	1977 HB	Ap	17.1M	mh	1.2	Sq	14.904	0.22–0.42		0.84
2100	Ra–Shalom	1978 RA	At	16.07	0.13	2.5	Xc	19.79	0.35–0.41	0.31	0.72
2102	Tantalus	1975 YA	Ap	16.2	m	3.3	Q	2.391	0.07–0.09		
2201	Oljato	1947 XC	Ap	16.86	0.24	2.1	Sq	24	>0.1		
2212	Hephaistos	1978 SB	Ap	13.87M	mh	3.3	SG	20	~0.1	0.41	0.77
2340	Hathor	1976 UA	At	19.2M	mh	5.3	Sq			0.50	0.77
2368	Beltrovata	1977 RA	Am	15.21M	mh	0.5		5.9	0.84	0.52	0.83
2608	Seneca	1978 DA	Am	17.52M	0.16	0.9	S	8	0.35	0.41	0.83
3102	Krok	1981 QA	Am	15.6	m	1.6	S	147.8	1.0	0.52	0.83
3103	Eger	1982 BB	Ap	15.38	0.53	2.5	E	5.709	0.72–1.5		
3122	Florence	1981 ET3	Am	14.20	0.20	2.5	S	2.35812	0.18		
3199	Nefertiti	1982 RA	Am	15.10	0.41	1.8	Sq	3.0207	0.11–0.30	0.38	0.95
3200	Phaethon	1983 TB	Ap	14.32	0.11	5.1	B,F	3.57	0.11–0.26		
3288	Seleucus	1982 DV	Am	15.34	0.17	2.8	S	75	>0.4	0.50	0.82
3352	McAuliffe	1981 CW	Am	15.8	0.18	2.4	S	3.	0.10		
3360		1981 VA	Ap	16.3M	0.07	1.8					
3361	Orpheus	1982 HR	Ap	19.03	m	0.5		3.58	0.32		
3362	Khufu	1984 QA	At	18.27	0.16	0.7					
3551	Verenia	1983 RD	Am	16.75M	0.53	0.9	V	4.93		0.39	
3552	Don Quixote	1983 SA	Am	13.0M	0.02	18.7	D	7	0.5		
3554	Amun	1986 EB	At	15.82M	0.17	2.1	M	2.5300	0.19	0.24	0.71
B3671	Dionysus	1984 KD	Am	16.7	0.16	1.5	Cb	2.705	0.15–0.26		
B3671	Dionysus	1984 KD	Am					27.72			
3691	Bede	1982 FT	Am	14.9M	m	3.6	Xc			0.44	
3752	Camillo	1985 PA	Ap	15.5M	m	2.7		37.846	1.1		
3753	Cruithne	1986 TO	At	15.13	mh	3.3	Q	27.44	0.4–0.95		
3757		1982 XB	Am	18.95	0.34	0.4	S	9.12	0.20	0.51	0.85
3838	Epona	1986 WA	Ap	15.4	m	2.9		4.762	0.04–0.37		
3908	Nyx	1980 PA	Am	17.4M	0.23	0.9	U	4.4257	0.11–0.44	0.44	
3988		1986 LA	Am	18.2M	m	0.8		8			
4015	Wilson–Harri	1979 VA	Ap	15.99	0.05	2	CF	3.556	0.06–0.2		
4055	Magellan	1985 DO2	Am	14.8M	0.24	3	V			0.52	
4179	Toutatis	1989 AC	Ap	15.3	0.13	2.8	S,Sq	129.84	1.2	0.50	0.85
4183	Cuno	1959 LM	Ap	14.4M	mh	4.5	Q,Sq	3.560	0.1–0.84		
4197		1982 TA	Ap	14.88	0.33	1.7	Sq	3.5400	0.28	0.4	0.75
4341	Poseidon	1987 KF	Ap	15.5M	mh	2.5	O	6.262	0.08		
4503	Cleobulus	1989 WM	Am	16.02	m	2.7		3.13	0.22		
4660	Nereus	1982 DB	Ap	18.3	d	1.2	C	15.1	0.6		
4688		1980 WF	Am	19.0M	0.18	0.6	SQ			0.45	0.94
4769	Castalia	1989 PB	Ap	16.9	m	1.4		4.086	0.64–1.0		
4947	Ninkasi	1988 TJ1	Am	18.7M	mh	0.6	Sq				
4953		1990 MU	Ap	14.1M	mh	3.6	S	14.218	0.70		
4954	Eric	1990 SQ	Am	12.6M	mh	9.5	S	12.056	0.57–0.66		
4957	Brucemurray	1990 XJ	Am	15.1M	mh	3.0	S	2.8921	0.10–0.38		
5131		1990 BG	Ap	14.1M	mh	4.7	S				
5143	Heracles	1991 VL	Ap	14.0M	mh	5.0	O	15.8	>0.1		
5324	Lyapunov	1987 SL	Am	15.2M	m	3.1				0.37	0.81
5332		1990 DA	Am	13.9M	mh	5.2	S	5.803	0.35		0.87
5370	Taranis	1986 RA	Am	15.7M	m	2.5			0.02		
5587		1990 SB	Am	13.6M	mh	6.5	Sq	5.052	0.80–1.25		

TABLE 1. (continued).

Asteroid Number*	Name	Provisional Designation	Group	H (mag)†	Albedo‡	Diameter (km)§	Class¶	Period (hrs)	Amplitude (mag)	U-B	B-V
B5407		1992 AX	MC	13.7	mh	5.8	Sk	2.549	0.11		
B5407		1992 AX	MC					13.5	0.35		
5620		1990 OA	Am	17.0M	m	1.4			1.2		
5626		1991 FE	Am	14.7M	mh	3.6	S	2.4860	0.07		
5646		1990 TR	Am	16.05	m	2.1	U	6.25	0.19		
5653	Camarillo	1992 WD5	Am	15.4M	m	2.9		4.8341	0.85		
5660		1974 MA	Ap	15.7M	mh	2.3	Q				
5693		1993 EA	Ap	16.82	mh	1.4	Q		0.13		
5751	Zao	1992 AC	Am	14.93	m	3.5	X	21.7	0.04–0.12	0.29	0.81
5797	Bivoj	1980 AA	Am	19.1M	mh	0.5	S	2.706	0.10–0.17	0.37	0.81
5836		1993 MF	Am	15.03	mh	3.1	S	4.959	0.53–0.76		
5863	Tara	1983 RB	Am	15.5M	m	2.7			>0.02		
6037		1988 EG	Ap	18.7M	m	0.6		4.27	0.2		
6047		1991 TB1	Ap	17.0M	mh	1.2	S				
6053		1993 BW3	Ap	15.23	0.18	3.1	Sq	2.57341	0.45		0.99
6063	Jason	1984 KB	Ap	15.3M	0.16	1.4	S				
6178		1986 DA	Am	15.1M	0.14	2.3	M	3.58	0.10–0.40		
6455		1992 HE	Ap	13.8M	mh	5.4	S				
6489	Golevka	1991 JX	Ap	19.074	0.63	.35 × .25 × .25	Q	6.02640	0.28–1.05		
6491		1991 OA	Am	18.5M	m	0.7		2.69	0.09		0.7
6569		1993 MO	Am	16.2	mh	1.8	Sr	5.9588	0.98		
6611		1993 VW	Ap	16.5M	h	1.2	V				
7025		1993 QA	Ap	18.3M	m	0.8		2.50574	0.32		
7092	Cadmus	1992 LC	Ap	15.4M	d	4.5	C				
7236		1987 PA	Am	18.4M	d	1.1	C				
7335		1989 JA	Ap	17.85	m	0.9					
7336	Saunders	1989 RS1	Am	18.7M	mh	0.6	Sq	6	0.3		
7341		1991 VK	Ap	16.7M	mh	1.4	Sq	4.20960	0.28–0.70		
7358		1995 YA3	Am	14.4M	mh	4.5	Sq	2.75	0.1–0.5		
7474		1992 TC	Am	18.3	m	0.8	X	5.540	0.07		
7480	Norwan	1994 PC	Am	17.45	mh	1.1	S	35.90	0.5		
7482		1994 PC1	Ap	16.8M	mh	1.4	S	2.5999	0.29		
7753		1988 XB	Ap	18.6M	d	1.0	B				
7822		1991 CS	Ap	17.4M	0.25	0.9	S	2.389	0.27–0.32		
7888		1993 UC	Ap	15.3M	mh	3.1	S	2.340	0.10		
7889		1994 LX	Ap	15.3	h	3.1	V	2.741	0.32–0.39		
7977		1977 QQ5	Am	15.4M	mh	2.6	S	7.46	0.56		
8013		1990 KA	Am	17.31	m	1.2		6	0.5		
8034		1992 LR	Am	17.9M	mh	0.8	S	3.638	0.46–0.52	0.47	0.84
8176		1991 WA	Ap	17.1M	mh	1.2	Q	8.3	1.0		
8201		1994 AH2	Ap	16.3	m	2.2	O	23.949	0.3–0.4		
8566		1996 EN	Ap	16.5M	m	1.7	U				
9162		1987 OA	Ap	18.3M	d	1.2	B				
9400		1994 TW1	Am	14.8M	mh	3.4	Sr				
9856		1991 EE	Ap	17.0	0.30	1	S	3.045	0.14		
9969	Braille	1992 KD	MC	15.8M	mh	2.2	Q				
10115		1992 SK	Ap	17.0M	m	1.4		7.320	0.70–1.01		
10165		1995 BL2	Ap	17.1M	m	1.3	L				
10302		1989 ML	Am	19.5	m	0.6	X	15.786	0.6–1.0		
10563	Izhdubar	1993 WD	Ap	17.33	mh	1.2	Q	2.660	0.17		
11066	Sigurd	1992 CC1	Ap	15.00	mh	3.2	S	8.4958	1.02		
11311	Peleus	1993 XN2	Ap	16.5M	mh	1.6	Sq				
11398		1998 YP11	Am	16.27	m	1.9		38.61	0.22		
11405		1999 CV3	Ap	15.0M	m	3.4		5.78	0.25–0.4		
11500		1989 UR	Ap	18.43	mh	0.7	S	73.0	0.46		
12711		1991 BB	Ap	16.04	mh	2.1	Sr	3.48	0.6		
12923		1999 GK4	Ap	16.1M	m	2.1		3.892	0.18		
13651		1997 BR	Ap	17.6M	mh	0.9	S	33.644	1.2		
14402		1991 DB	Am	18.4M	0.16	1.1	B	2.266	0.1		
14827		1986 JK	Ap	18.3M	d	1.2	C				
15817	Lucianotesi	1994 QC	Am	18.6M	m	0.7	X	11.	0.8		
16064		1999 RH27	Am	16.9M	d	2.5	C	178.6	0.6		
16636		1993 QP	Am	17.50	m	1.2		22.05	0.23		
16657		1993 UB	Am	16.9M	mh	1.3	Sr				
16834		1997 WU22	Ap	15.7M	mh	2.3	S	9.348	0.4		
16960		1998 QS52	Ap	14.3	mh	4.3	Sq				
17274		2000 LC16	Am	16.7M	m	1.6		16.495	0.35		
17511		1992 QN	Ap	17.1M	m	1.3	X	5.9902	1.1		
18882		1999 YN4	Am	16.3M	mh	1.7	S				
19356		1997 GH3	Am	17.1M	mh	1.2	S	6.714	0.74		
20086		1994 LW	Am	16.9M	m	1.5		29.1	0.28		
20236		1998 BZ7	Ap	17.6M	mh	1.0	Q	10.17	0.15		
20255		1998 FX2	Am	18.2M	mh	0.7	Sq	6.826	0.22		
20429		1998 YN1	Ap	18.0M	m	0.9		2.72	0.1		
22753		1998 WT	Ap	17.7M	mh	0.9	Q				

TABLE 1. (continued).

Asteroid Number*	Name	Provisional Designation	Group	H (mag)†	Albedo‡	Diameter (km)§	Class¶	Period (hrs)	Amplitude (mag)	U-B	B-V
23548		1994 EF2	Am	17.6M	mh	0.9	Q				
23714		1998 EC3	Am	16.7M	mh	1.4	Q	1.2	0.25		
25143		1998 SF36	Ap	19.2M	0.32	0.36	S(IV)	12.15	1.0		
27002		1998 DV9	Ap	18.2M	mh	0.7	Q				
29075		1950 DA	Ap	17.0M	m	1.4		2.1216	0.2		
B31345		1998 PG	Am	17.64	(0.16)	0.9	Q	2.516	0.11		0.81
B31345		1998 PG	Am					7.003	0.09		
31346		1998 PB1	Am	17.1M	mh	1.2	Q				
33342		1998 WT24	At	17.9M	0.42	0.5	E	3.6977	0.3		
B35107		1991 VH	Ap	16.5	mh	1.4	Sk	2.624	0.08		
B35107		1991 VH	Ap					32.69			
35432		1998 BG9	Am	19.5M	mh	0.4	S				
36017		1999 ND43	Am	19.2M	mh	0.5	Sl	>5	>0.5		
36183		1999 TX16	Am	15.61	m	2.7	Ld	5.611	1.3		
B38071		1999 GU3	Am	19.6M	m	0.4		4.49			
B38071		1999 GU3	Am					9.03d			
		1977 VA	Am	19.0M	m	0.5	XC			0.15	0.7
		1978 CA	Ap	18.0M	h	0.6	M	3.756	0.8	0.14	0.72
		1988 TA	Ap	20.8M	d	0.4	C				
		1989 DA	Ap	18.6M	m	0.7		3.925	0.12		
		1989 UP	Ap	20.5M	m	0.3		6.98	1.16		
		1989 UQ	At	19.0M	d	0.9	B	7.733	0.27		
		1989 VA	At	17.89	mh	0.8	Sq	2.51357	>0.15–0.4		
		1989 VB	Ap	19.82	m	0.4		16,24	>0.32		
		1990 HA	Ap	16.74	m	1.5		8.58	>0.09		
		1990 SA	Am	17.0M	mh	1.2	S				
		1990 UA	Ap	19.64	m	0.4		6.25?	>0.1		
		1990 UP	Am	20.45	m	0.3		20.	0.8		
		1991 AQ	Ap	17.20	mh	1.1	Q,U				
		1991 VA	Ap	26.5M	m	0.02			0.4		
		1991 XB	Am	18.10	mh	0.9	SX				
		1992 BF	At	19.5M	m	0.4	Xc				
		1992 NA	Am	16.5M	d	2.7	C	6.992	0.42		
		1992 UB	Am	16.0M	m	2.1	X				
		1993 BX3	Ap	21.0M	m	0.2		20.463	0.91		
		1993 TQ2	Am	20.0M	mh	0.3	Sa				
		1994 AB1	Am	16.3M	mh	1.7	Sq				
		B1994 AW1	Am	17.5	mh	1.0	Sa	2.519	0.3		
		B1994 AW1	Am					22.40			
		1994 CB	Ap	21.0M	m	0.2		8.676	>0.90		
		1994 GY	Am	17.0M	m	1.4		2.5553	0.06		
		1994 TF2	At	19.3	mh	0.4	S				
		1995 BC2	Am	17.3M	m	1.2	X				
		1995 CR	At	21.5M	mh	0.16	S	2.42			
		1995 EK1	Ap	18.0M	m	0.9		8.444	0.45		
		1995 FJ	Ap	20.5M	m	0.3		9.2	0.3		
		1995 FX	Am	20.0M	m	0.3		5.46	0.2		
		1995 HM	Am	22.5	m	0.11		1.62	2.		
		1995 WL8	Am	18.1M	mh	0.8	Sq				
		1996 BZ3	Am	18.2M	m	0.8	X				
		B1996 FG3	Ap	17.76	m	1.6	X	3.594	0.08		0.71
		B1996 FG3	Ap					16.1	0.25		
		1996 FQ3	Am	21.0M	mh	0.2	Sq				
		1996 JA1	Ap	21.1	0.30	0.2	V	5.227	0.39–0.8		
		1997 AC11	At	21.0M	m	0.2	Xc				
		1997 AQ18	Ap	18.2M	d	1.2	C				
		1997 BQ	Ap	18.0M	mh	0.8	S				
		1997 GL3	Ap	20.0M	h	0.2	V				
		1997 MW1	At	19.2M	m	0.5	X				
		1997 NC1	At	18.0M	d	1.4	B				
		1997 QK1	Am	20.1M	mh	0.3	SQ				
		1997 RT	Am	20.0M	mh	0.3	Q				
		1997 SE5	Am	14.8M	m	3.8	T	9.0583	0.23		
		1997 TT25	Am	19.3M	mh	0.4	Sq				
		1997 UH9	At	18.8M	mh	0.5	Sq	>5	0.15		
		1997 US9	Ap	17.3M	mh	1.2	Q	3.58	0.2		
		1997 VM4	Ap	18.0M	mh	0.8	SQ				
		1998 BB10	Ap	20.4M	mh	0.3	Sq				
		1998 BT13	Ap	26.5M	mh	0.02	Sq				
		1998 FM5	Am	16.0M	mh	2.2	S	6.35	1.0		
		1998 HD14	At	20.9M	mh	0.2	SQ				
		1998 HE3	At	21.8M	mh	0.1	SQ				
		1998 KU2	Am	16.6	d	2.6	F,Cb				
		1998 KY26	Ap	25.5M	d	0.04	CP	0.178	0.30		
		1998 ME3	Am	19.3M	d	0.7	F				
		1998 ML14	Ap	17.6	mh	1.2	Q,S	14.98	0.12		

TABLE 1. (continued).

Asteroid Number*	Asteroid Name	Provisional Designation	Group	H (mag)†	Albedo‡	Diameter (km)§	Class¶	Period (hrs)	Amplitude (mag)	U-B	B-V
		1998 MQ	Am	16.6	mh	1.5	S				
		1998 MT24	Ap	14.8M	m	4.0	X	12.07	0.38		
		1998 MW5	Ap	19.2M	mh	0.5	Sq				
		1998 MX5	Am	18.1M	m	0.8	X				
		1998 QA1	Ap	19.1M	d	0.8	C				
		1998 QC1	Ap	19.6M	d	0.7	C				
		1998 QH2	Ap	16.1M	mh	1.9	Q				
		1998 QK28	Ap	19.5M	d	0.7	C				
		1998 QP	Ap	21.5M	m	0.2		5.4	0.1		
		1998 QR15	Am	18.0M	mh	0.9	Sq	2.46	0.1		
		1998 QR52	Ap	18.7M	m	0.6		235.	0.8		
		1998 QV3	Am	20.5M	mh	0.2	Q				
		1998 SG2	Am	19.7M	mh	0.4	Sq				
		B1998 ST27	At	19.5M	m	0.4					
		1998 ST49	Ap	17.7M	mh	0.9	Q				
		1998 TU3	At	14.7M	mh	3.6	Q				
		1998 UT18	Ap	19.1M	d	0.9	G	34	0.8		
		1998 VD31	Ap	19.1	mh	0.5	S				
		1998 VO	Ap	20.4	mh	0.3	S				
		1998 VO33	Ap	16.9	h	1.0	V	8.5	0.24		
		1998 VR	At	18.5	mh	0.6	Sk				
		1998 WB2	Ap	22.8	mh	0.12	S	0.313	0.6		
		1998 WM	Ap	16.8	mh	1.4	Sq				
		1998 WP5	Am	18.4M	mh	0.7	Sl				
		1998 WZ1	Ap	19.9M	mh	0.3	Q				
		1998 WZ6	Ap	17.3	h	0.8	V				
		1998 XA5	Am	18.8M	m	0.6			0.22		
		1998 XS16	Ap	16.46	m	1.7		5.421	1.4		
		1999 CF9	Ap	17.8M	mh	0.9	Q				
		1999 DJ4	Ap	18.5M	mh	0.6	Sq				
		1999 EE5	Am	18.4M	mh	0.7	S				
		1999 FA	Ap	20.7M	mh	0.3	S	10.09	1.2		
		1999 FB	Ap	18.1M	mh	0.8	Q				
		1999 GJ4	Ap	14.97	mh	3.2	Sq	4.956	1.0		
		B1999 HF1	At	14.5M	m	4.3	EMP	2.3191	0.10–0.12		0.72
		B1999 HF1	At					14.02			
		1999 JD6	At	17.2M	m	1.2	K	7.68	1.2		
		1999 JE1	Ap	19.5M	mh	0.4	Sq				
		1999 JM8	Ap	15.15	m	3.3		137.	0.7		
		1999 JO8	Am	17.0M	mh	1.4	S	2.386	0.11		
		1999 JU3	Ap	19.6M	d	0.7	Cg				
		1999 JV3	Ap	19.0M	mh	0.5	S				
		1999 JV6	Ap	19.9M	m	0.4	Xk				
		B1999 KW4	At	16.6M	m	1.6		2.61	0.2		
		B1999 KW4	At					17.5			
		1999 NC43	Ap	16.0M	mh	2.0	Q				
		1999 PJ1	Am	18.0M	m	0.9		6.201	1.1		
		1999 RB32	Am	19.8M	h	0.3	V				
		1999 RQ36	Ap	20.9M	m	0.2		2.146	0.22		
		1999 SE10	m	20.0M	m	0.3	X				
		1999 SF10	Ap	24.0	m	0.06		0.0411	0.58		
		1999 SK10	Ap	19.3M	mh	0.4	Sq				
		1999 SM5	Ap	19.07	m	0.54		6.230	0.77–0.96		
		1999 TA10	Am	17.77	m	1.0		14.	0.1		
		1999 TY2	Ap	23.1	mh	0.08	S	0.121	0.68		0.94
		1999 VM40	Am	14.60	mh	3.8	S	5.185	0.25–0.36		
		1999 VN6	Am	19.5M	d	0.7	C				
		1999 WK13	Am	17.2M	mh	1.1	S				
		1999 XO35	Am	16.8M	mh	1.4	Sq				
		1999 YB	Am	18.5M	mh	0.6	Sq				
		1999 YD	Am	21.1M	mh	0.2	Sk				
		1999 YF3	Am	18.5M	mh	0.6	Sq				
		1999 YG3	Ap	19.1M	mh	0.5	S				
		1999 YK5	At	16.8M	m	1.5	X				
		2000 AC6	At	21.0M	mh	0.2	Q				
		2000 AG6	Ap	25.3M	m	0.03		0.077	0.8		
		2000 AX93	Am	17.7M	mh	0.9	Sq				
		2000 AE205	Am	22.9M	mh	0.08	S				
		2000 AH205	Ap	22.4M	mh	0.1	Sk				
		2000 DO8	Ap	24.8M	m	0.04		0.022	1.39		
		B2000 DP107	Ap	18.2M	m	0.8		2.7755			
		B2000 DP107	Ap					42.23			
		2000 EB14	At	23.0M	m	0.09		1.79	1.7		
		2000 EE14	At	17.1M	mh	1.2	Q				
		2000 ES70	Am	17.1M	mh	1.2	S				
		2000 ET70	At	18.4M	m	0.7	X				

TABLE 1. (continued).

Asteroid Number*	Asteroid Name	Provisional Designation	Group	H (mag)†	Albedo‡	Diameter (km)§	Class¶	Period (hrs)	Amplitude (mag)	U-B	B-V
		2000 EV70	Ap	19.7	mh	0.4	Q				
		2000 EW70	At	21.1	d	0.3	F				
		2000 GK137	Ap	17.4M	m	1.1		4.84	0.27		
		2000 HB24	At	23.3M	m	0.08		0.218	0.24		
		2000 JG5	Ap	18.3M	m	0.8		6.055	1.0		
		2000 JQ66	Am	18.1M	m	0.8		11.11	0.6		
		2000 NM	Ap	15.6M	m	2.6		9.24	0.3–0.5		
		2000 OG8	Am	17.8M	m	1.0		4.07	0.1		
		2000 PH5	At	22.6M	m	0.1		0.2029	0.85		
		2000 QW7	Am	19.8M	m	0.37		long	0.04		
		2000 RD53	Am	20.1M	m	0.33		14.79	0.10		
		2000 SM10	Ap	24.1M	m	0.05		15.	0.2		
		2000 SS164	Am	16.7M	m	1.6		6.894	0.9		
		B2000 UG11	Ap	20.4M	m	0.3					
		B2000 UG11	Ap					0.809 d			
		2000 WH10	Ap	22.5M	m	0.11		0.023	0.25		
		2000 WL107	Am	24.8	m	0.038		0.322	1.2		
		2000 YA	Ap	23.6M	m	0.07		1.33	0.35		
		2001 CB21	Ap	18.5M	m	0.7		3.30	0.19		
		2001 CP36	At	23.7M	m	0.06		10.	0.05		
		2001 OE84	Am	17.8M	m	0.9		0.4865	0.60		
		B2001 SL9	Ap	17.5M	m	1.1		2.40	0.08		
		B2001 SL9	Ap					16.4	0.08		
		2002 BM26	Ap	20.1M	m	0.3		2.7			

* "B" before an asteroid number indicates a possible binary asteroid. For such objects, a second line gives the orbital period (if known) and the lightcurve amplitude contribution of the binary.
† "M" within this column indicates the value is from the Minor Planet Center (http://cfa-www.harvard.edu/cfa/ps/mpc.html).
‡ When albedo is not estimated through physical measurements, an approximation is assigned based on the taxonomic class. These assumed albedos are coded as follows: d for "dark" (0.06), m for "medium" (0.15), mh for "medium high" (0.18), h for "high" (0.30). "m" is assigned in the case of no taxonomic information.
§ When diameter is not directly measured or determined through physical measurements, as is the case for all objects assigned an albedo code, the diameter (D, in km) is estimated from the following relationship (*Fowler and Chillemi,* 1992): $2 \log(D) = 6.247 - 0.4\,H - \log(\text{albedo})$.
¶ Taxonomic class. See text in section 2 for the conventions used.

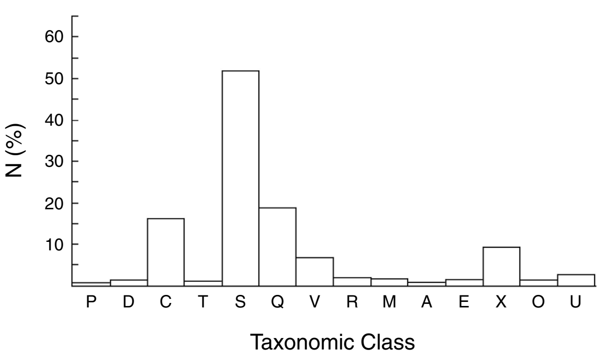

Fig. 2. Histogram of the relative proportions of measured taxonomic properties for more than 300 NEOs listed in Table 1. Almost all taxonomic classes seen among main-belt asteroids are represented within the NEO population. As detailed by *Luu and Jewitt* (1989), strong selection effects favor the discovery and characterization of higher-albedo objects such as S-type (and possibly Q-type) asteroids. Within this histogram, the designation "C" includes both C-types and related subgroups (B, F, G). Those having unusual characteristics that do not fall into any present category, or classes (such as L, K) having <1% representation, are combined within the designation "U."

corrections are accounted for, a clear signature for a dominant contribution from the inner asteroid belt remains. *Benedix et al.* (1992), *Lupishko and Di Martino* (1998), and *Whiteley* (2001) all find that after applying bias-correction factors to the observed NEO population, at any given size there are relatively equal proportions of C- and S-type objects within near-Earth space. However the main belt, in its entirety, is dominated by C-types. [A bias-correction analysis of the main belt performed by *Zellner* (1979) suggests that C-types dominate among all main-belt asteroids by as much as 5:1.] The fact that C-types do not dominate the NEO population (even after strong bias correction) indicates that asteroidal NEOs are not being contributed equally by all regions of the main belt. Thus the inner regions of the asteroid belt, where S-types are most common (*Gradie and Tedesco,* 1982; *Gradie et al.,* 1989) must preferentially contribute to the NEO population. *Benedix et al.* (1992) point out that the region of the 3:1 resonance has roughly equal populations of C- and S-type asteroids in its vicinity, making it a compatible source. Dynamical models (e.g., *Migliorini et al.,* 1998; *Morbidelli and Nesvorný,* 1999; *Vokrouhlický et al.,* 2000; *Bottke et al.,* 2000, 2002a; *Morbidelli et al.,* 2002) certainly support the view of the 3:1 resonance and inner asteroid belt dominating the contributions to the near-Earth population.

General taxonomic and spectral links between the main belt and near-Earth populations have been proposed since the beginning of substantial studies of NEO properties (*McFadden et al.,* 1984, 1985). Unique taxonomic classifications and mineralogic interpretations do show evidence for specific ties to main-belt sources. Most notable among these is the E-type object 3103 Eger, which appears both compositionally and dynamically related to the Hungaria region (high-inclination objects) of the inner asteroid belt (*Gaffey et al.,* 1992). These authors also argue for a connection to the enstatite achondrite meteorites. Basaltic (pyroxene-rich) NEOs having V-type taxonomies and good spectral matches to both the howardite-eucrite-diogenite (HED) classes of meteorites and Vesta were found by *Cruikshank et al.* (1991). The existence of numerous main-belt asteroid fragments apparently excavated from Vesta (*Binzel and Xu,* 1993; *Thomas et al.,* 1997) and the dynamic viability of their delivery into the inner solar system (*Migliorini et al.,* 1997) provides an additional specific link between the main belt and NEOs. Perhaps the objects of most practical interest (from the hazard-assessment and resource-utilization points of view) among the NEOs are the M-types that may be highly metallic in composition (*Tedesco and Gradie,* 1987). The most notable case among NEOs, confirmed as metallic by virtue of its extremely high radar albedo, is (6178) 1986 DA (*Ostro et al.,* 1991). Nevertheless, confirmed M-types and (presumably) highly differentiated, olivine-rich A-types are relatively rare among the NEOs.

3.2. Relationships of Near-Earth Objects to Comets

While taxonomic and mineralogic characterization of NEOs provide confident links to main-belt origins, cometary origins are suggested with substantially less certainty as described in *Weissman et al.* (2002). Most supply models have broadly considered asteroid and comet sources (e.g., *Wetherill,* 1988; *Bottke et al.,* 2002a), and some analyses (e.g., *Rabinowitz,* 1997a,b) suggest that comets may not be required at all as a major contributor to the population. Direct imaging (e.g., *Luu and Jewitt,* 1992*)* through the discovery and followup process to date has not revealed any other NEO case like that of the dual comet/asteroid citizenship of 4015 Wilson-Harrington (*Fernandez et al.,* 1997). Analysis of images of more than 100 NEOs by *Whiteley* (2001) constrains most of these objects to have production rates 1–2 orders of magnitude lower than weakly active comets such as P/Arend-Rigaux and P/Neujmin 1 (*Campins et al.,* 1987; *Jewitt and Meech,* 1985).

Nevertheless, interesting cases among the NEOs leave the issue open. Cases to be resolved include the meteor-stream association for 3200 Phaethon (*Whipple,* 1983; *Williams and Wu,* 1983; *Cochran and Barker,* 1984; *Fox et al.,* 1985); unusual spectral and possible magnetic signatures from 2201 Oljato (*McFadden et al.,* 1993); and the intermittent cometary properties of 4015 Wilson-Harrington (*Fernandez et al.,* 1997). While the taxonomic classifications (neutrally colored F and CF designations; Table 1) for 3200 Phaethon and 4015 Wilson-Harrington appear consistent with primitive solar-system materials presumed to dominate in comets, the classifications (Sq and SU;Q) for Oljato and Icarus are more like inner main-belt asteroids and do not seem to make "cometary sense." D-type asteroids such as 3552 Don Quixote and 1997 SE5 (*Hicks et al.,* 1998, 2000), however, do add to the list of NEOs having taxonomic characteristics that make them extinct comet candidates.

3.3. Relationships of Near-Earth Objects to Ordinary-Chondrite Meteorites

As described in *Burbine et al.* (2002), measurements of the spectral properties of NEOs have been revealing toward the problem of finding sources for the most common class of meteorites, the ordinary chondrites. *Clark et al.* (2002) outline the considerable debate over whether the most commonly observed asteroids, the S-types, are related to the most common meteorites (see also *Wetherill,* 1985; *Wetherill and Chapman,* 1988). Here we briefly describe and illustrate the role of NEO physical studies toward achieving an understanding that appears to be forging a link between S-type asteroids and ordinary-chondrite meteorites. This link is most likely for a subset of S-type asteroids denoted as S(IV) (*Gaffey et al.,* 1993). Overall, the mineralogy of asteroids across the entire S-class appears to be diverse (see *Gaffey et al.,* 2002).

The proximity of NEOs provides the opportunity for measuring the physical properties of objects in the size range (roughly 10–100 m) of most meteorite precursors. Spectral measurements over a continuity of sizes from meteoroids to main-belt asteroids appears to show a transition between S-type asteroids and ordinary-chondrite meteorites. The tendency toward seeing "ordinary-chondrite-like" spectral properties among S-types at smaller and smaller sizes (measured within the NEO population) has been noted in multifilter color measurements (*Rabinowitz et al.,* 1998; *Whiteley and Tholen,* 1999; *Whiteley,* 2001) and in visible and NIR CCD spectra (*Binzel et al.,* 1996, 1998, 2001). Figure 3 illustrates the trend in spectral properties between S-type asteroids and ordinary-chondrite meteorites revealed by NEO spectral measurements.

Several plausible explanations can be offered for the trend toward ordinary chondritelike spectral properties with decreasing diameter. The first is that spectral variations are due to particle-size effects (*Johnson and Fanale,* 1973), where the decreasing surface gravity results in a different size distribution of regolith and ~1-μm-sized particles on the surface. (These are the particle sizes most responsible for absorption, reflection, and scattering of visible and NIR wavelengths measured by reflectance spectroscopy.) A variety of photometric parameters are indicative of surface particle sizes, as we discuss in section 3.4. However, these parameters show no evidence for a diameter dependence, thereby giving doubt to a surface particle-size explanation for the trend in S-type asteroid spectral properties.

A second explanation is related to the average surface age of smaller bodies (*Binzel et al.,* 1998). Survival lifetimes against catastrophic disruption (see *Davis et al.,* 2002) decrease with decreasing size. Thus, on average, as we examine smaller and smaller objects, we see younger and younger surfaces. If time-dependent surface-alteration processes are effective [e.g., space weathering; see *Clark et al.*

(2002)] the smallest objects will have on average the youngest, freshest, and least-altered surfaces. The finding that smaller S-type NEOs have spectral properties tending increasingly toward those of "fresh" ordinary-chondrite meteorite specimens is fully consistent with the occurrence of a space-weathering process. In our view, the reality of a space-weathering process is strongly supported by the elemental-abundance measurements of Eros made by the *NEAR Shoemaker* spacecraft (*Trombka et al.,* 2000; *McCoy et al.,* 2001; *Cheng,* 2002). These *NEAR Shoemaker* results support the conclusion that Eros, a rather typical S-type NEO, has the same elemental abundance as ordinary-chondrite meteorites, except for a deficiency of S (perhaps explained by solar-wind sputtering). It has become increasingly accepted that the most likely way to reconcile these elemental-abundance results with the mismatch between telescopic spectra of Eros and laboratory spectra of ordinary chondrites is for some space-weathering-like surface alteration process to be active on S-type asteroid surfaces.

There are notable objections to the above idea, however, some of which are described in *Whiteley* (2001). The most significant objection is that S-type asteroids can still be found among very small NEOs, some so small that their collisional lifetimes are 5–10 m.y. or less. There also exist 5-km NEOs that are spectrally very good matches to OC meteorites and that have collisional lifetimes of 0.5–1.0 b.y. If the spectral signatures of SQ-type asteroids are dominated by a strong temporal weathering trend, we should expect to see no (or very few) S-type spectra among the collisionally "youngest" asteroids. There is also some spectral evidence in *Pravec et al.* (2000a) that there are S-types among the monolithic fast-rotating asteroids. This is a significant complication for the space-weathering hypothesis, because such asteroids rotate too quickly to retain a regolith, and thus should be the least-weathered asteroids we can observe. It remains to be seen whether some size-dependent petrological process, or the consideration of more sophisticated surface-age models, would help resolve these contradictions.

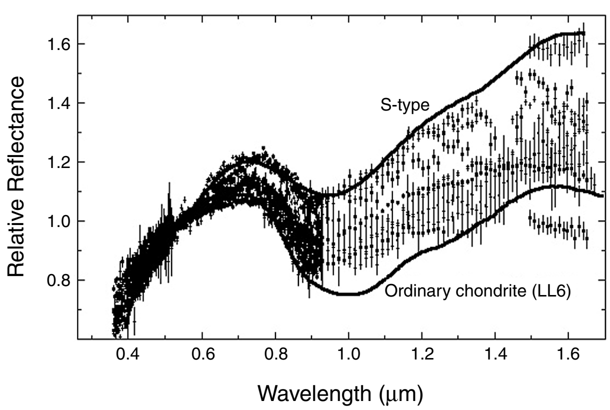

Fig. 3. An apparently continuous distribution of spectral properties is seen between the most commonly observed S-type asteroids and the most common class of meteorites, the ordinary chondrites. One possible explanation is a size-dependent trend where smaller NEOs have (on average) younger and fresher surfaces that have not been subjected to possible space-weathering effects. Thus their spectral properties are most likely to resemble those for meteorites measured in the laboratory. [NEO data from *Binzel et al.* (2001); meteorite data from *Gaffey* (1976).]

Regardless of the exact nature of the relationship between S- and Q-type asteroids, Fig. 4 illustrates that the once-scarce matches between NEOs and ordinary-chondrite meteorites are now increasingly common. As Fig. 2 depicts, ~20% of all observed NEOs have spectral properties placing them in the taxonomic class Q. [Q class asteroids have spectra most similar to laboratory spectra of ordinary-chondrite meteorites (*McFadden et al.,* 1984; *Bus et al.,* 2002).] How do we reconcile that ordinary chondrites, which account for ~80% (by fall statistics) of all meteorites, are derived from objects that seem to account for only 20% of the NEO population? While achieving a rigorous quantitative agreement between these proportions is not yet within our grasp, we can qualitatively conceive a bridge across this disparity. As a first step, we can understand that the higher relative strength of ordinary-chondrite material, compared to more primitive carbonaceous material, will create some amount of overrepresentation of ordinary-chondrite material in our total sample. [In the extreme case of the strongest objects, a vastly greater proportion of iron meteorites populate our collections than their likely abundance in near-Earth space (*Lipschutz et al.,* 1989).] A second qualitative step we can recognize is that the *NEAR Shoemaker* elemental-abundance results for Eros (*Trombka et al.,* 2000; *McCoy et al.,* 2001) suggest the common S-type asteroids (such as Eros) may have ordinary chondritelike compositions. Thus, if ordinary chondrites are in fact derived from S-type (and not just Q-type) asteroids, qualitatively it appears possible to reconcile the high proportion of ordinary-chondrite meteorite falls with the supply of objects in near-Earth space.

3.4. Shapes and Rotations

The shapes and rotation rates of small objects, such as NEOs, arise from a variety of factors. NEOs derived from the asteroid belt are almost certainly second- (or multi-) generation collision fragments from once-larger parent bodies (see *Davis et al.,* 2002). Asteroids in the size range of a few tens of kilometers, or smaller, are not large enough for self-gravity to protect them from catastrophic disruption over the age of the solar system. Just as NEOs are relatively recent (and transient) visitors to the inner solar system, most have shapes and rotations that have been reworked on a timescale short compared with 4.5 b.y. (see *Paolicchi et al.,* 2002). Collision processes have also been active on the cometary component (if any) that contributes to the NEO population, where *Durda and Stern* (2000) calculate that comet nuclei having NEO-like sizes (smaller than 5 km) have also undergone substantial collisional processing since the time of original formation.

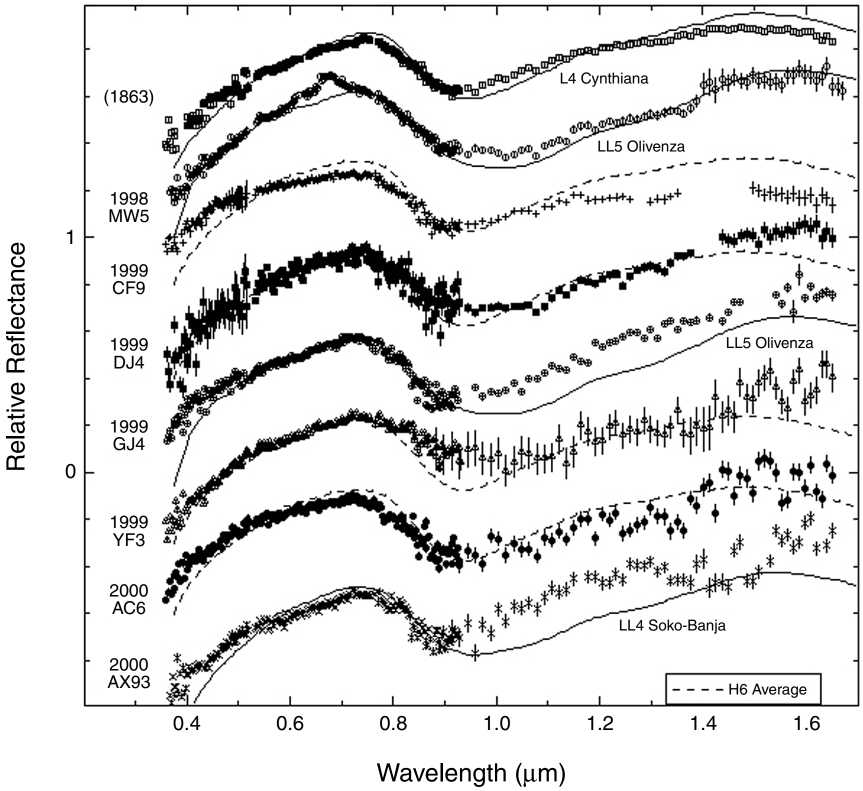

Fig. 4. A decade ago, only one NEO [1862 Apollo (*McFadden et al.,* 1985)] was known to have spectral properties resembling ordinary-chondrite meteorites. At present about 20% of all measured NEOs provide a plausible match to ordinary chondrites, with several examples illustrated here. [NEO data from *Binzel et al.* (2001); meteorite data from *Gaffey* (1976).]

An important result bearing on the collisional (and hence shape and rotation) evolution of NEOs comes from the crater statistics on Eros revealed by the *NEAR Shoemaker* mission (*Veverka et al.,* 2000). These results suggest that at some time since Eros entered near-Earth space, it has been effectively decoupled from the collisional environment of the main belt (*Michel et al.,* 1998). Thus, the shapes and rotations seen for NEOs (with exceptions noted below) may be most strongly determined by the processes occurring at their place of origin. If this is the case, then the shapes and perhaps rotations seen for NEOs that come from the asteroid belt should be representative of what we would observe in the asteroid belt at these small diameters if our observational techniques allowed. Analysis of the YORP (Yarkovsky-O'Keefe-Radzievskii-Paddack) effect by *Rubincam* (2000), however, points out the possibility of anisotropic thermal emission dominating the spin states of kilometer-sized bodies. Thus, the YORP effect might decouple the spin rates for most kilometer-sized asteroids from their initial state at the time of formation. Unfortunately, it is currently below the capabilities of most facilities to measure the detailed physical properties of main-belt asteroids below the size range of 5–10 km.

There is an observational suggestion that asteroidal NEOs are indeed similar in rotation and shape to their comparably sized main-belt counterparts. Using rotational lightcurves to convey information on spin period and approximate shape, Table 2 compares NEOs with two diameter (D) ranges of main-belt asteroids. The first group attempts to provide a comparison for NEOs by using the subset of main-belt asteroids having D < 2 km, approximating (as closely as possible with available data) the size range of NEOs. The second group simply contains the lightcurve characteristics of large (D > 130 km) main-belt asteroids. The sample size for these main-belt groups, and for the NEOs, is more than 100 objects in each case. Because NEOs are typically observed at large phase angles, all data have been reduced to their expected lightcurve amplitudes at 0° solar-phase angle, following the method of *Zappalà et al.* (1990). Table 2 shows that both the reduced-lightcurve amplitudes and the rota-

TABLE 2. Mean values of asteroid amplitudes and rotation rates.

Population	⟨D⟩ (km)	Observed Amplitude (mag)	N	Reduced Amplitude (mag)	Rotation Rate (rev/d)	N
NEOs	2.9 ± 0.5	0.49 ± 0.04	118	0.29	4.80 ± 0.29	119
MBAs (D < 12 km)	6.8 ± 0.3	0.35 ± 0.03	102	0.28	4.34 ± 0.23	100
MBAs (D > 130 km)	186 ± 1	0.22 ± 0.01	100	0.19	2.90 ± 0.12	100

tion rates are statistically indistinguishable between NEOs and the D < 12 km main-belt asteroids. These results give us confidence that the rotation and shape characteristics of asteroidal NEOs are reasonable proxies for similar diameter main-belt asteroids. Among the unusual complexities revealed are a nonprincipal axis rotation for 3288 Seleucus, 4179 Toutatis, 1994 AW1, and 4486 Mithra (see *Pravec et al.,* 2002; *Ostro et al.,* 2002; also *Lupishko and DiMartino,* 1998, and references therein). Super-fast rotators (having periods between 2 and 20 min) have been revealed through a variety of observations (e.g., *Steel et al.,* 1997; *Ostro et al.,* 1999; *Pravec et al.,* 2000a; *Whiteley et al.,* 2002). *Pravec and Harris* (2000) and *Whiteley et al.* (2002) demonstrate that these fast-spinning objects are beyond the rotational breakup limit for aggregates with no tensile strength ("rubble piles") for bulk densities plausible for asteroids.

How well can rotation and shape data distinguish those NEOs that may be of cometary origin? By definition, objects labeled as comets have comae that substantially increase the difficulty of directly measuring the comparable physical properties of their nuclei. Yet those comets that have been measured typically have axial ratios that would produce rotational lightcurves whose amplitude of brightness variation would be in the range of 0.5–1.0 mag (*Hartmann and Tholen,* 1990; *Luu*, 1994; *Nelson et al*. 2001), substantially larger than the 0.29 value estimated for asteroidal NEOs in Table 2. Thus, elongated shapes may provide some suggestion, when combined with dynamical and compositional factors, for discerning NEOs as having a cometary origin. Similarly, *Binzel et al.* (1992) find that slower rotations might also indicate cometary NEOs. However, we emphasize that rotation and shape alone are not sufficient by themselves to conclusively reveal a cometary origin for an individual NEO.

An unresolved question at this time is whether the relatively common occurrence of binary objects among NEOs (*Pravec and Harris,* 2000) is especially intrinsic to the NEO population. Table 1 in *Merline et al.* (2002) lists the detailed properties of the handful of NEOs that (to date) have been revealed to be binary.

NEOs that suffer close encounters with Earth could be distorted into particularly elongated shapes, and these tidal distortions could play a role in forming binaries (*Bottke et al.*, 1996, 1999; *Richardson et al.,* 1998). However, the discovery of binaries within the main-belt population [e.g., 762 Pulcova and 90 Antiope (*Merline et al.,* 2000)] indicates that the process or processes that form them are not unique to the NEO population. These processes are examined in *Paolicchi et al.* (2002).

3.5. Optical Properties and Surface Structure

The small diameters (young age, low surface gravity), proximity, and possibly diverse origins of the NEOs make an understanding of their surface properties a topic of broad interest. A complete and extensive review of these properties is presented by *Lupishko and Di Martino* (1998). Here we present an updated summary.

TABLE 3. Mean optical parameters of S-type NEOs and S-type main-belt asteroids (all wavelength-dependent measurements are with respect to the V band).

Parameter	NEAs	N	MBAs (D > 100 km)	N
Albedo polarimetric	0.183 ± 0.011	9	0.177 ± 0.004	28
Albedo radiometric	0.190 ± 0.014	23	0.166 ± 0.006	27
U-B (mag)	0.445 ± 0.013	30	0.453 ± 0.008	28
B-V (mag)	0.856 ± 0.013	31	0.859 ± 0.006	28
β (mag/deg)	0.029 ± 0.002	9	0.030 ± 0.006	18
P_{min} (%)	0.77 ± 0.04	3	0.75 ± 0.02	28
h (%/deg)	0.098 ± 0.006	9	0.105 ± 0.003	23
α_{inv} (deg)	20.7 ± 0.2	6	20.3 ± 0.2	18

Table 3 compares the surface properties for large main-belt asteroids and NEOs which have S-type asteroid reflectance properties. These parameters include the polarimetric and radiometric albedos, color indices, phase coefficients β_V, and polarimetric parameters such as depth of negative polarization P_{min}, polarization slope h, and inversion angle α_{inv} [for the definition of these parameters see *Dollfus et al.* (1989)]. The table indicates that the smaller S-type NEOs may have higher albedos on average, a result consistent with a limited amount of thermal measurements and modeling of NEOs (see *Harris and Lagerros,* 2002). One explanation for the difference in albedo as a function of diameter (and presumably surface age) could be a space-weathering effect (see *Clark et al.,* 2002). If space weathering involves only a coating of grains [as proposed by *Pieters et al.* (2000)], then only measurements sensitive to spectral colors (and not particle size) would show a diameter-dependent effect. However, we note that because the albedo difference is suggested more strongly in the radiometric data than in the polarimetric data, thermal properties of the surfaces of these smaller bodies (and our success in modeling them) may play a role in creating this effect.

Interestingly, the characterization of the surface properties most sensitive to particle sizes as measured through the parameters β_V, P_{min}, h, and α_{inv} reveals no systematic differences across significant diameter ranges, suggesting that at least the majority of the S-type NEOs have the same surface porosity and roughness at the submicron scale as their larger diameter counterparts in the main belt (*Helfenstein and Veverka,* 1989). A comparison of Hapke parameters between NEOs, main-belt asteroids, and satellites (Table 4) shows similar results: Very few differences appear to be present at microscales across a broad range of diameters. Qualitatively, this may be understood as arising from the fact that numerous forces are at work on micrometer-sized particles. Gravity (and hence diameter dependence) may be relatively inconsequential compared with electrostatic forces and Poynting-Robertson drag (*Lee,* 1996). Thus, the relative presence (or absence) and structure of micrometer-sized particles on the surfaces of asteroids and NEOs may be quite independent of size.

Macroscale (centimeter and larger) differences in surface properties, however, become apparent when comparing small NEOs with large main-belt asteroids. The circular-

TABLE 4. Hapke parameters of NEOs and other small bodies.

Object	Data	Particle Albedo w	Oppostion Surge Width h	Oppostion Surge Amplitude Bo	Asymmetry Parameter g	Microscopic Roughness θ (deg)	Reference
Eros	NEAR	0.44 ±0.044	0.03 ±0.003	1.0 ±0.1	–0.31 ±0.031	28 ±2.8	*Clark et al.* (2000)
Geographos	EB,rad	≥0.22	0.02	1.32 ±0.10	–0.34 ±10	25	*Hudson and Ostro* (1999)
Apollo	EB	0.318 ±0.004	0.034 ±0.007	0.90 ±0.02	–0.32 ±0.01	15 ±1	*Helfenstein and Veverka* (1989)
Toutatis	EB	0.261 ±0.019	0.036 ±0.023	1.20 ±0.32	–0.29 ±0.06	32 ±8	*Hudson and Ostro* (1998)
Castalia N	EB	0.384 ±0.07	—	—	–0.11 ±0.09	46 ±10	*Hudson et al.* (1997)
Castalia S	EB	0.239 ±0.07	—	—	–0.30 ±0.09	25 ±10	*Hudson and Ostro* (1998)
Golevka	EB	0.58 ±0.03	0.0114 ±0.0004	0.758 ±0.014	–0.435 ±0.001	7 ±7	*Mottola et al.* (1997)
Golevka	rad	0.173 ±0.006	0.024 ±0.012	1.03 ±0.45	–0.34 ±0.02	20 ±5	*Hudson et al.* (2000)
Phobos	VK	0.070 ±0.020	0.055 ±0.025	4.0 +6–1	–0.08*	22 ±2	*Simonelli et al.* (1998)
Deimos	VK	0.079 +0.008 –0.006	0.068 +0.082 –0.037	1.65 +0.90 –0.61	–0.29 ±0.03	16 ±5	*Thomas et al.* (1996)
Ida	EB,GL	0.218 +0.024 –0.005	0.020 ±0.005	1.53 ±0.10	–0.33 ±0.01	18 ±2	*Helfenstein et al.* (1996)
Dactyl	GL	0.211 +0.028 –0.010	⟨0.020⟩	⟨1.53⟩	–0.33 ±0.03	23 ±5	*Helfenstein et al.* (1996)
Gaspra	EB,GL	0.360 ±0.07	0.060 ±0.01	1.63 ±0.07	–0.18 ±0.04	29 ±2	*Helfenstein et al.* (1996)

*Effective value for two-term Henyey-Greenstein phase function.

EB = Earth-based (V filter); GL = *Galileo* (GRN filter); VK = Viking (clear filter); NEAR = *NEAR Shoemaker* (0.55 μm); rad = radar observations.

polarization ratio of radar echo power denoted as SC:OC (see *Ostro et al.,* 2002) is diagnostic of surface roughness at scales of the radar wavelength and wave penetration depth. If the SC:OC ratio is very low, the surface should be smooth at scales within an order of magnitude of the radar wavelength (*Ostro,* 1989). The higher mean ratios depicted in Table 5 show that the surfaces of NEOs are much rougher than those of larger-diameter main-belt asteroids at the scale length of decimeters and meters. Asteroid 433 Eros is at present the only NEO for which we have *in situ* images of the surface at centimeter to meter scales, and thus Eros provides some perspective on what these surfaces may be like (*Veverka et al.,* 2001). NEOs on average have rougher surfaces than Eros. However, Eros has an SC:OC value (Table 5) that places it intermediate between NEOs and main-belt asteroids. In addition to their higher mean, the SC:OC ratios of individual NEOs show tremendous diversity and span ~1 order of magnitude, from 0.09 [(6178) 1986 DA, 2.3-km, M-type] to 1.0 (2101 Adonis, 3103 Eger, 1992 QN). Thus among the smallest objects, surfaces range from being highly smooth to incredibly rough. While surface roughness of main-belt asteroids and NEOs are different on average, comparable values of radar albedo (Table 5) imply similar bulk densities and porosities of surface materials.

TABLE 5. Mean radar albedos and circular polarization ratios of NEAs and main-belt asteroids.

Sample	⟨D⟩ km	Radar Albedo	N	SC/OC	N
433 Eros	13 × 13 × 33	0.20 ± 0.01	1	0.22 ± 0.06	1
NEAs, S-type	6.3 ± 2.7	0.16 ± 0.02	15	0.31 ± 0.03	17
MBAs, S-type	136.5 ± 12.2	0.15 ± 0.01	14	0.14 ± 0.02	10
NEAs, all types	4.9 ± 1.8	0.18 ± 0.02	24	0.36 ± 0.04	36
MBAs, all types	179.8 ± 27.3	0.15 ± 0.01	36	0.11 ± 0.01	22

4. CONCLUSIONS AND FUTURE WORK

Achieving an understanding of the population of NEOs provides insights into a broad range of solar-system processes. Progress has been made in recognizing the processes for delivering material to the vicinity of Earth, where dynamical studies and physical measurements show independent and consistent evidence for the inner asteroid belt as a primary source. While the cometary contribution remains uncertain, great progress has been made toward identifying sources for ordinary-chondrite meteorites among the near-Earth population. Key directions for future research include pinpointing more precisely and quantitatively the sources for NEOs. Work also remains to be done for quantitatively reconciling meteorite-fall statistics with the population of objects that intersects the Earth. All evidence points to asteroidal NEOs being representative of similarly sized objects in the main belt. From an exploration perspective, this correlation presents a convenient opportunity to study the diversity of main-belt compositions (such as through sample-return missions) with the comparative ease and convenience of operating in near-Earth space. For these scientific reasons, and for the pragmatic reasons of hazard and resource assessment, NEOs will remain a continuing focus for solar-system small-body research in the decades ahead.

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